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Final Report

Critical Survey of Plasma Processing

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Summary

Low temperature plasmas represent an expansive region in the density-temperature parameter space of experimentally generated plasmas. With densities ranging from 10^6 to 10^{17} cm^{-3}, and temperatures ranging from 10^{-2} to 10 eV, these plasmas exhibit a variety of collective behaviours, supporting many physical states and interactions among the particle species within the plasma. It is precisely this variety in physical conditions that lends the plasma environment so well to the myriad of applications that have developed in plasma processing. These applications are exampled by; processing of solid state materials by ion implantation, thin film deposition, plasma enhanced chemical vapor deposition, plasma etching and also applications involving hardening and improving wear and corrosion resistance of refractory metals and composites. These applications have enjoyed great advancement in technological development. Much of this advancement is very system dependent and does not enjoy the fundamental scientific underpinning evident in other disciplines. The absence of this strong theoretical foundation is not only of interest for the aesthetics of academic inquiry of poorly understood systems, but also of interest due to the practical benefit of industrial technology expansion. Both, system process optimization and cross disciplinary transfer of technology would be aided by a strengthening in the understanding of the foundation that supports technological advances. This increased understanding can form the basis of expanding beyond existing system specific parameters and providing for process optimization and design.

In the following we shall discuss the results of the literature survey and investigation of the following topics, Plasma formation, Characterization and Modeling, and Key opportunities.

I. Plasma Formation

Plasma formation for processing requires, reproducible and controllable production of plasma species with system parameters appropriate for the specific processing application. The plasmas produced in high current discharges through gases, exploding wires and imploding pinch devices, have several applications. These applications include, use as a plasma opening switch (POS), plasma erosion opening switch (PEOS) and use as an x-ray radiation source. Plasma switches play an important roll in high energy, pulse power devices in which hundreds of GW to TW of power must be electrically switched or transferred on times scales of tens of nanoseconds to milliseconds. This has been demonstrated on short time scales on capacitive generators and long time scales on inductive generators. It has been found both experimentaly and through simulation that the conduction current on the short time scale is proportional to the plasma density. For longer conduction times the current scales as $I_c \alpha n^x$, with $0.25 < x < 0.5$. For the longest of conduction times the current co[illegible]uction depends on the physics of plasma erosion which may be domin[illegible] by magnetic forces in the current channel, J x B, collisional excitation and charge exchange processes with neutral species and even pre-conditioning effects of the plasma switch surfaces.

Plasmas formed by ionization with electromagnetic waves have a wealth of applications, including plasma enhanced chemical vapor deposition (PECDV), plasma immersion ion implantation (PI I I), plasma etching and surface sputtering. In these configurations, a radio-frequency signal is used to energize the low pressure gas to the plasma state. The mature development of standard rf sources and the variety of, cavity modes, shapes and sizes of electrodes leads to design

flexibility in the efforts to meet specific processing needs. The ability to impose, in addition, an external magnetic field yields access to electron cyclotron resonance excitation of the plasma and the attendant energy and spatial selectivity of the affected species. This selectivity is important for control of ion energy and flux to the processed surface and also important because of the spatial uniformity needed for very large scale integration (VLSI). Control of these parameters will impact etching and deposition rates, film modifying properties and minimize surface damage.

II) Plasma Characterization and Modeling

The high energy, high current of plasmas used as plasma opening switches, exploding wire and implosion of gas puffs, have enjoyed sustained years of experimental success. The advances in characterizing experimental results have largely been computational. Computational developments can be broadly characterized as consisting of magnetohydrodynamic modeling of the plasma dynamics and radiation transport, with local theromodynamic equilibrium (LTE), or some variant there of, to model the radiative emissions. Exceptions to this generlalization have some non-equilibrium model, or kinetic theory for the radiative processs and includes atomic transitions and collisional exitations. While analytic models are the norm for kinetic theories of radiation emission, some models employ computational constructs op particle in cell (PIC) codes or Monte Carlo codes to describe the nonequilibrium properties.

The rf generated plasmas contains several active areas of research modeling. Particularly noteworth is the description of the bulk plasma motion and its interaction with the sheath plasma that surrounds the electrodes. Of interest in this regard is the conduction current transported through the sheath, and the

energy distribution of the ions that reach the electrode surface. On long time scales as compared to the ion plasma oscillations, $t >> \omega^{-1}_{pi}$, the conduction current reaches the quasistatic value given by the Childs- Langmuir law,

$$J = (4/9)\, \varepsilon_o\, (2\, e/ M\,)^{1/2}\, V_o^{3/2}\, s_o^{-2}\ .$$

Where ε_o is the electro-permittivity of free space, e is the electronic charge, M is the mass of the ion, s_o is the thickness of the sheath and V_o is the voltage drop across the sheath. On shorter time scales than the ion plasma oscillation, the electrons which are oscillating in the rf field can separate from the ionic species and form a local potential gradient referred to as the ion matrix potential. It is this potential that is responsible for the acceleration of the ions through the sheath, and the subsequent bombardment of the electrode surface. The reason that obtaining an accurate model of the potential is important, is because it will determine the distribution of ion energies that will strike to electrode surface. Even though the dominant interaction among the species is collisional, some processing applications depend on the introduction of chemically reactive species into the plasma. The associated reaction rates and surface chemistry results are dependent on the energy distribution and population of the reactants.

III. Key Opportunities

A key area of plasma processing research that is ripe for expansion is that of modeling the plasma dynamics and sheath evolution in rf generated plasmas. This area is of interest, both because of the rapid expansion and availability of ECR plasma reactors for processing, and also because of the similarity in methods of analysis with other non-neutral plasma acceleration and radiative problems familiar to the author. This area of research has enjoyed many

successes in the estimate of gross sheath dimensions and potential drop, yet these models fail to adequately describe the deviations from the Child-Langmuir law. Furthermore, the predicted scalings of conduction current with respect to the ratio of sheath voltage to applied rf voltage and the ratio of electrode surface areas does not conform to the experimental observations. While some of these discrepancies may be due to some of the modeling assumptions, such as no electrons in the sheath region, mono-energetic ions, Maxwellian electron distributions and collisionless ions in the sheath region, the predominant deficiency is in the lack of self-consistency in the coupling of the nonlinear equations which describes the system. The required advance seems intractable in the analytic sense, but well with computational capabilities. This enhanced model should include multi-species evolution of the electron, ion and neutral distributions, with kinetic treatment of the stochastic heating, collisional excitation of the plasma.

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